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SLIDING MODE CONTROL OF A CLASS OF UNCERTAIN DYNAMIC SYSTEMS USING LINEAR MATRIX INEQUALITY APPROACH

NOR LAILI BINTI MAHMUD

A project report submitted in partial fulfillment of the
requirements for the award of the degree of
Master of Engineering (Electrical- Mechatronics and Automatic Control)

Faculty of Electrical Engineering
University Technology Malaysia

NOVEMBER 2007

DECLARATION

I declare that this research project report entitled "*Sliding mode control of a class of uncertain dynamic systems using linear matrix inequality approach"* is the result of my own research except as cited in the references. The report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, my supervisor, researchers, my friends and family. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my project supervisor, Assoc. Prof. Dr. Mohamad Noh Ahmad for his encouragements, guidances, critics and friendship. He has been a great help to me as he is always constantly monitoring my progress, giving me suggestion to solve the problem that I encountered and for being available anytime I need help in my project.

I am also indebted to Universiti Teknologi Malaysia (UTM) for giving me a chance to do this research project and for it's assistance in supplying the relevant literatures. I am also very thankful to my fellow postgraduate students for their guidance, advices and motivation. Without their continued support and interest, this report would not have been the same as presented here. My sincere appreciation also extends to Encik Abdul Rashid and others who have provided assistance at various occasions. Their views and tips are useful indeed.

I would also like to sincerely thank my family who provided me with financial aid, support, understanding and encouragement. Finally, I would also like to take this opportunity to thank all lecturers for their teachings, advices and suggestions. Once again, I would like to sincerely thank all the people that are mentioned above.

ABSTRACT

Over the year, many researchers have considered the problem of stabilizing the uncertain systems. In variable structure control (VSC) system, the controller structure around the plant is intentionally changed by using a viable high-speed switching feedback control to obtain a desired plant behavior or response. In this project, the problem of designing a variable structure control (VSC) law for uncertain system is considered. Using LMI approach, a design method of a linear sliding surface which is linear to the state is developed. A sufficient condition for the existence of linear sliding surface is given in term of LMIs and an explicit formula of linear sliding surfaces guaranteeing the quadratic stability of the reduced-order equivalent system dynamics restricted to the sliding surfaces is derived. The sliding mode controller is then applied to an Electrohydraulic servo system. The simulation works were performed using MATLAB/SIMULINK software. A comparison with Pole Placement method shows that the sliding mode controller designed using LMI method produce a better performance responses.

ABSTRAK

Sejak bertahun lamanya, para penyelidik cuba mencari penyelesaian untuk masalah penstabilan sistem yang tak pasti. Kawalan Struktur Berubah telah dicipta untuk mengatasi masalah ini. Di dalam projek ini, Kawalan Mod Gelongsor, yang merupakan salah satu cabang dari Kawalan Struktur Berubah, telah digunakan untuk menstabilkan sistem yang tak pasti. Menggunakan cara Ketidaksamaan Matrik Datar, Matrik Permukaan Gelongsor diperolehi dan di gunakan di dalam Kawalan Mod Gelongsor yang kemudian di masukkan ke dalam model sistem Elektrohidraulik. Sistem ini kemudian di simulasikan menggunakan perisian MATLAB/SIMULINK. Perbandingan dengan cara Peletakan Pole menunjukkan Kawalan Mod Gelongsor yang di cipta menggunakan cara Ketidaksamaan Matrik Data menghasilkan reaksi system yang lebih bagus, berprestasi tinggi dan tegap.

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REFERENCES

Boyd, S., Balakrishnan, V., Feron, E. and El Ghaoui, L. (1994a). History of Linear Matrix Inequalities in Control Theory. *American Control Conference*. Vol. 1, 31-34.

Boyd, S., Balakrishnan, V., Feron, E. and El Ghaoui, L. (1994b). *Linear Matrix Inequalities in System and Control Theory*: Society for Industrial and Applied Mathematics.

Chen, Chi-Tsong. *Analog and Digital Control System Design: Transfer Function, State-Space, and Algebraic Methods*. Saunders College Publishing.

Choi, Han Ho (1998). An Explicit Formula of Linear Sliding Surfaces for a Class of Uncertain Dynamic Systems for a Class of Uncertain Dynamic Systems with Mismatched Uncertainties. *Automatica.* Vol. 34*,* No. 8, 1015-1020.

Chu, E. K. and Datta, B. N. (1996). Numerically Robust Pole Assignment for Second Order Systems. *International Journal of Control.* Vol. 64, 1113-1127.

Decarlo, A., Raymond, Zak, Stanislaw, H. and Matthews, P. Gregory (1998). Variable Structure Control of Nonlinear Multivariable Systems: A Tutorial. *IEEE Transactions- Automatic Control.* Vol. 76, No. 3.

Dorf, R.C. (1992). *Modern Control Systems.* New York: Addison-Wesley.

Edwards, C. and Spurgeon, S.K. (2003). Linear Matrix Inequality Methods for Designing Sliding Mode Output Feedback Controllers. *IEE Proceedings-Control Theory Applications.* Vol. 150, No. 5.

Fung, Rong-Fong and Yang, R-T. (1997). Application of VSC in Position Control of a Nonlinear Electrohydraulic Servo System. *Pergamon.* Vol 66, No. 4, 365-372.

Ha, Q. P., Nguyen, H. Q. and Durrant-Whyte, H.F. (1998). Sliding Mode Control with Fuzzy Tuning for an Electrohydraulic Position Servo System. *2nd International Conference on Knowledge-Based Intelligent Electronic Systems*.

Hussain, A.R., Ahmad, M.N. and Mohd. Yatim, A.H. (2007). Sliding Mode Control with Linear Quadratic Hyperplane Design: An application to an Active Magnetic Bearing System. *The 5th Student Conference on Research and Development-SCOReD.*

Hwang, C.L. (1996). Sliding Mode Control using Time-varying Switching Gain and Boundary Layer for Electrohydraulic Position and Differential Pressure Control. *IEE Proc.-Control Theory Appl.* Vol. 143, No. 4.

Merrit, Herbert E. (1976). *Hydraulic Control System*. New York: Wiley.

Rafidah Ngadengon (2005). *A Full-order Sliding Mode Tracking Controller Design for an Electrohydraulic Control System*. University Technology Malaysia: Master Thesis.

Spurgeon, S.K. and Edwards, C. (1998). *Sliding Mode Control: Theory and Applications*. London: Taylor and Francis.

Xiang, Ji., Su, Hongye and Chu, Jian (2005). Robust Sliding Mode Output Feedback Control Design Using ILMI Approach. *American Control conference,* 8-10.